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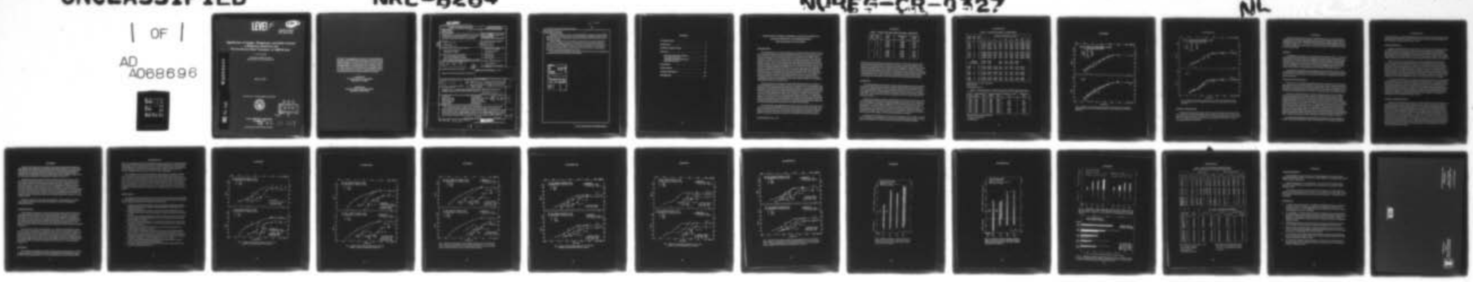

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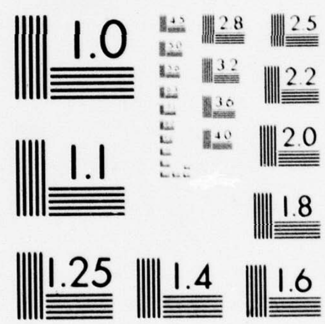

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Significance of Copper, Phosphorus, and Sulfur Content to Radiation Sensitivity and Postirradiation Heat Treatment of A302-B Steel

J. R. HAWTHORNE

Thermostructural Materials Branch
Material Science and Technology Division

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The effects of three levels of copper content and phosphorus content and two levels of sulfur content on radiation sensitivity and postirradiation heat treatment response were explored for a reactor pressure vessel steel, Type A302-B. Test plates for the investigation were produced from 182-kg (400-lb) laboratory melts. The contributions of individual elements were assessed from Charpy-V (C_v) notch ductility changes with 288°C (550°F) irradiation and with a 343°C (650°F)-168 h postirradiation heat treatment. Limited studies of properties recovery by postirradiation 399°C (750°F) heat

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treatment were also made.

Radiation embrittlement sensitivity, as shown by C_v transition-temperature elevation and C_v upper-shelf reduction, generally increased with increased copper and phosphorus content and with decreased sulfur content. Certain ranges of phosphorus and copper content were found to be more critical than others.

Response to 343° C (650° F) postirradiation heat treatment, as evidenced by transition temperature recovery in degrees C, appeared to be independent of copper, phosphorus, and sulfur content for the ranges investigated. Response to heat treatment also appeared to be independent of the magnitude of the prior transition-temperature elevation by irradiation. On the other hand, a dependence of percentage recovery on impurity-element content was observed. A dependence of upper-shelf recovery on copper content was also found.

Six of the eight plate compositions exhibited full upper-shelf recovery but only small transition-temperature recovery after 343°C (650°F) heat treatment.

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CONTENTS

SIGNIFICANCE OF COPPER, PHOSPHORUS, AND SULFUR CONTENT TO RADIATION SENSITIVITY AND POSTIRRADIATION HEAT TREATMENT OF A302-B STEEL

INTRODUCTION

The detrimental effect of neutron radiation on the notch ductility of steel is known to be accentuated by high copper and high phosphorus contents [1]. In current (new) reactor vessel construction, both impurities are being held to low levels in those regions where sensitivity to radiation is to be minimized [2]. For vessels built prior to 1971, copper and phosphorus contents were not specially limited by purchase specifications. The resulting variations in the content of these impurities have led to significant differences in apparent radiation resistance [2]. More importantly, the magnitude of projected reductions in notch ductility properties is such that the requirements of the ASME Code (Section III) [3] and the Code of Federal Regulations (10CFR50) [4], in many cases, may not be satisfied over planned vessel lifetimes. In particular, a present concern is upper-shelf energy retention throughout service. Projections for some vessels indicate that Charpy-V (C_v) upper-shelf values will fall below the ASME Code energy index of 68 J (50 ft-lb). This energy level is required to define the reference nil-ductility temperature, RT_{NDT}. Close estimation of upper-shelf values, however, has been difficult, since trends in upper-shelf reduction with irradiation are not well established for the fluence range of interest and contributing metallurgical variables are not fully known.

The present study was undertaken to help clarify the individual and joint roles of copper and phosphorus in C_v upper-shelf response to irradiation and to postirradiation heat treatment. In-situ postirradiation heat treatment (annealing) is one method currently being considered for the reduction of detrimental radiation effects to vessels should the need arise. While this method is sanctioned by the national design codes, its effectiveness for recovery has not been fully established for 288°C (550°F) radiation conditions typical of reactor vessel service. Trends in steel reembrittlement following heat treatment, i.e., reirradiation response, in particular have not been investigated in detail. The present study also evaluates sulfur as a third (suspect) impurity. Interest in this residual element stems from Äuger spectroscopy observations of high ($\geq$ 10%) sulfur concentrations on postirradiation fracture surfaces of welds having bulk concentrations on the order of 0.010% S [5].

The material test matrix designed for the study is shown in Table 1. The matrix centers on the base composition A302-B, which is typical of older reactor vessel steel plates. Composition variations include two levels of sulfur content and three levels each of copper and phosphorus content. For studies of recovery by postirradiation heat treatment, a 343°C (650°F)—168 h heat treatment was applied to all materials. Only partial embrittlement

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Table 1 — Design of Test Matrix (Base Composition A302-B Steel)

Melt No.	Cast No.	Sulfur (%)	Phosphorus (%)	Copper (%)
1	1	0.015	0.003	0.15
	2	0.015	0.015	0.15
	3	0.015	0.025	0.15
	4	0.015	0.025	0.30
2	1	0.025	0.015	0.03
	2	0.025	0.015	0.15
	3	0.025	0.015	0.30
	4	0.025	0.025	0.30

relief was expected with this heat-treatment temperature. On the other hand, the 168-h time period was specially selected to eliminate time as an experimental variable. (Prior studies have demonstrated that an extension of the heat treatment beyond 168 h has little effect toward additional recovery for 288°C (550°F) irradiation conditions.) Specimen numbers permitting, higher-temperature heat treatments were also evaluated. On this point, it is emphasized that the study focused on the exploration of material trends and impurity influences rather than on precise definitions of irradiation and heat-treatment effects. Accordingly, each determination was accomplished with as few specimens as possible.

MATERIALS

Two 182-kg (400-lb) vacuum melts were made. Split-melt procedures were employed to obtain the eight composition variations needed. Impurity additions, as required, were made to the melting furnace prior to the teeming of each ingot. The plates from melt No. 1 were designated Series V6X and contained 0.017% S; plates from melt No. 2 were designated Series V7X and contained 0.029% S. Phosphorus content was the primary variable in Series V6X; copper content was the primary variable in Series V7X. Plate chemistries are indicated in Table 2.

All plates were produced using a cross-rolling ratio of 5:1 and were heat treated under conditions designed to match the mechanical properties and microstructure of representative commercially produced plate, including the ASTM A302-B reference plate [1,6]. The heat treatment consisted of 899°C (1650°F) for 1 h and air cooling followed by 649°C (1200°F) for 1 h and water quenching. Yield and tensile strengths are given in Table 3. The plates show good correspondence in strength and conformance to A302-B steel strength specifications. Figures 1 and 2 compare C_v notch ductilities of the plates from Series V6X and V7X, respectively. Again, a close similarity of properties is observed.

In planning the investigations, it was expected that the plates would exhibit a relatively low C_v energy level in the transverse (TL, weak) test orientation before irradiation. Accordingly, the longitudinal (LT, strong) orientation was selected for irradiation studies.

Table 2 — Chemical Composition of A302-B Plates

Plate Code	Melt No.	Cast No.	Chemical Composition (wt %)[a]								
			S	P	Cu	C	Mn	Si	Mo	Al[b]	N
V61	1	1	0.017	0.002	0.15	0.23	1.38	0.26	0.50	0.028	0.001
V63	1	2	0.017	0.014	0.15	0.24	1.28	0.26	0.49	0.029	0.002
V65	1	3	0.017	0.024	0.16	0.24	1.36	0.26	0.50	0.029	0.001
V67	1	4	0.017	0.024	0.29	0.24	1.37	0.26	0.50	0.028	0.001
V71	2	1	0.029	0.016	0.045	0.25	1.23	0.25	0.49	0.027	0.001
V73	2	2	0.029	0.016	0.16	0.25	1.23	0.25	0.49	0.027	0.001
V75	2	3	0.029	0.016	0.30	0.25	1.23	0.25	0.49	0.027	0.001
V77	2	4	0.029	0.024	0.30	0.25	1.23	0.25	0.49	0.027	0.001
A302-B Specification			0.040 max.	0.035 max.	—	0.25 max.	1.15 1.50	0.15 0.30	0.45 0.60	—	—
40B	A	2[c]	0.021	0.006	0.002	0.24	1.33	0.23	0.54	0.033	—
40C	A	3[c]	0.022	0.021	0.008	0.23	1.30	0.21	0.53	0.031	—
38A	B	1[c]	0.004	0.003	0.002	0.24	1.34	0.27	0.54	0.032	—
38B	B	2[c]	0.004	0.004	0.20	0.24	1.34	0.24	0.54	0.028	—
39A	C	1[c]	0.003	0.004	0.002	0.26	1.24	0.21	0.54	0.026	—
39B	C	2[c]	0.005	0.004	0.20	0.25	1.25	0.20	0.53	0.021	—

[a]Ladle analyses by U. S. Steel Corporation

[b]Total aluminum

[c]Plate analysis by NRL [1]

Table 3 — Tensile Properties of A302-B Steel Plates (Ambient Temperature Tests)

Plate Code	Yield Strength[a] (MPa)	Yield Strength[a] (ksi)	Tensile Strength[b] (MPa)	Tensile Strength[b] (ksi)	Reduction of Area (%)	Elongation (%)
V61	528	76.5	664	96.4	-c-	-c-
V63	530	76.9	669	97.0	65.7	23.7
V65	531	77.0	671	97.3	65.7	24.8
V67	531	77.0	675	97.9	65.9	24.1
V71	533	77.4	674	97.7	-c-	-c-
V73	531	77.0	674	97.8	63.5	23.9
V75	537	77.9	677	98.2	63.5	24.5
V77	538	78.4	682	98.9	64.6	24.2

[a]6.4-mm (0.252-in.)-diameter specimens

[b]Average of duplicate tests

[c]Not determined

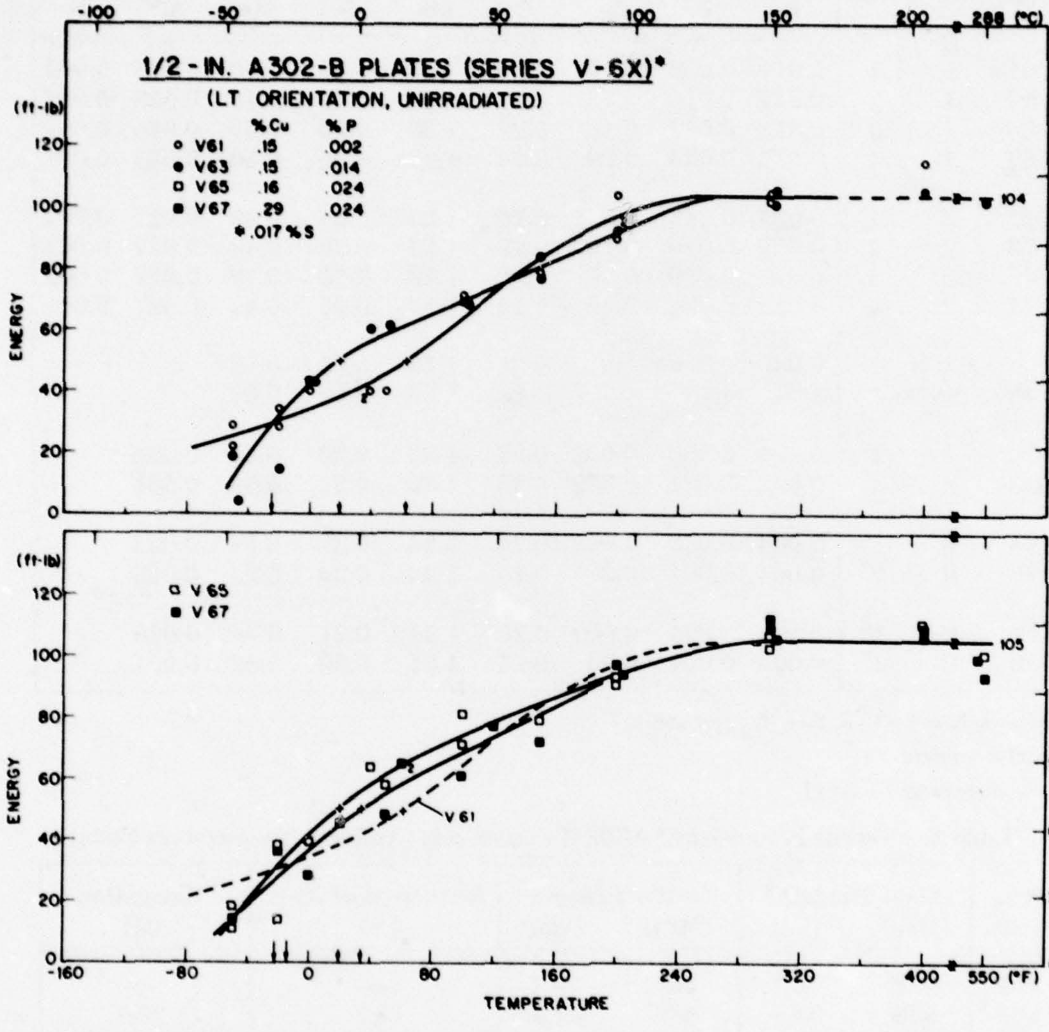

Fig. 1 — Charpy-V notch ductility of plate Series V6X (LT orientation) before irradiation. Upper-shelf values for the TL orientation (not shown) were in the range of 75 to 81 J (55 to 60 ft-lb).

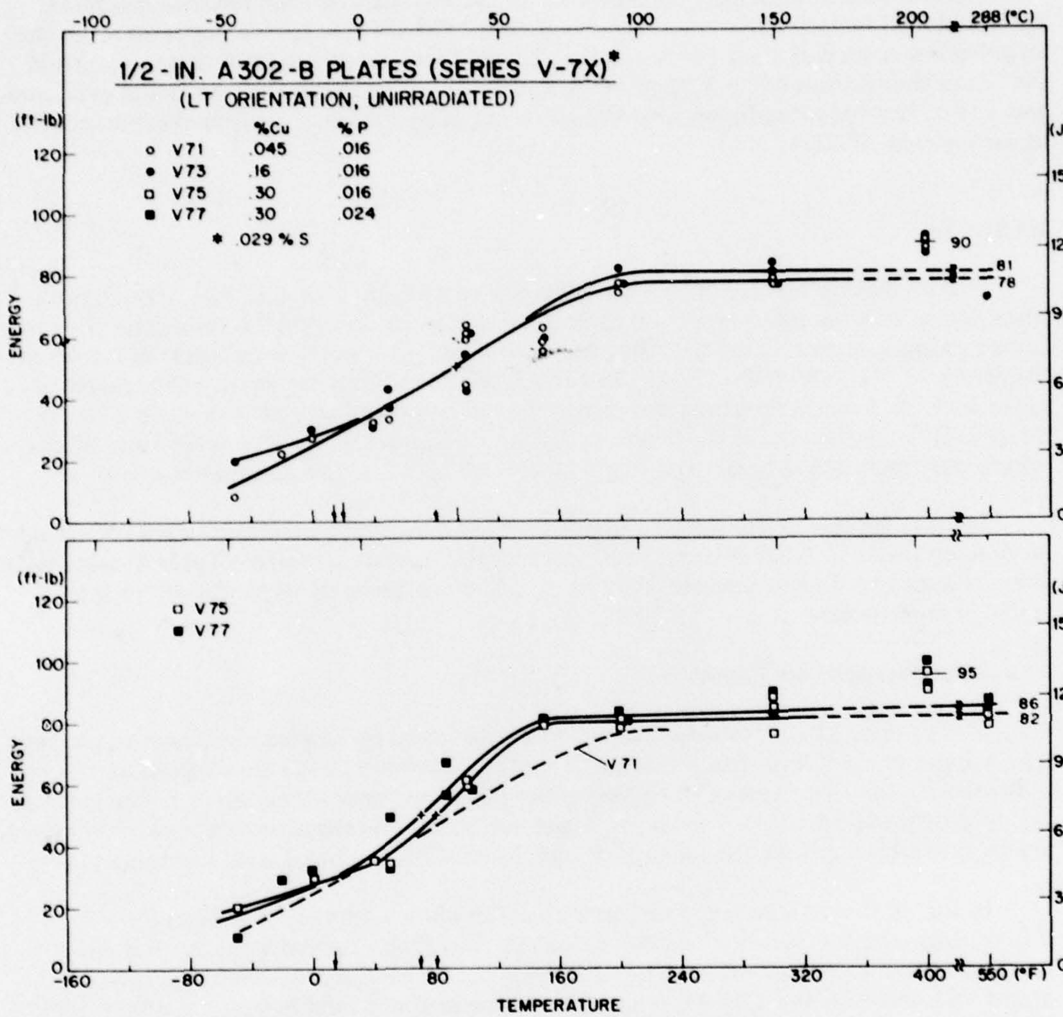

Fig. 2 — Charpy-V notch ductility of plate Series V7X (LT orientation) before irradiation. Upper-shelf values for the TL orientation (not shown) were in the range of 49 to 57 J (36 to 42 ft-lb).

MATERIAL IRRADIATION

The plates were irradiated at 288°C (550°F) in two simultaneous experiments in the State University of New York at Buffalo Reactor (UBR). Experiment No. 1 contained the plate Series V6X and plate V73; Experiment No. 2 contained the plate Series V7X and plate V67. The average neutron fluences were 3.1×10^{19} and 3.3×10^{19} n/cm^2 > 1 MeV (calculated spectrum), respectively.

Fluence determinations were based on measurements with iron neutron dosimeter wires included in each experiment specimen array. For the fuel lattice positions used, the calculated spectrum fluence (Φ^{cs}) and the fluence based on an assumed fission spectrum (Φ^{fs}) had the relation $\Phi^{cs} = 1.22\ \Phi^{fs}$ (>1 MeV). The duration of the irradiation exposure was 959 h. Irradiation temperatures were monitored by means of multiple thermocouples in each specimen array.

RESULTS

Postirradiation test results for the plate Series V6X are shown in Figs. 3 to 5; those for plate Series V7X are given in Figs. 6 to 8. Figures 9 to 12 and Table 4 summarize the observed changes in notch ductility after irradiation and after postirradiation heat treatment. Typically, C_v 41-J (30 ft-lb) and C_v 68-J (50 ft-lb) transition-temperature changes agree quite well. Differences in reported neutron fluences among plates are the result of small neutron-flux gradients over the length of the irradiation assembly. Plates V67 and V73, which were included in both experiments, show no effect of the fluence variation.

In planning this investigation and in analyzing the results, irradiation data for earlier laboratory melts of A302-B (plate) with controlled impurity levels (see Table 4) were taken into account [1]. In this manner, the test matrix was effectively expanded by four additional compositions.

Transition-Temperature Elevation

In Figs. 9 to 11 the transition-temperature elevation by irradiation is seen to increase with copper content and with phosphorus content. However, a lower radiation sensitivity is indicated for the plate series (V7X) having the higher sulfur content. An opposite trend for this impurity was anticipated from the Äuger study. An investigation of the radiation mechanism(s) involved and additional experiments to confirm the trend with sulfur are planned.

In Fig. 9, the data indicate that an increase in phosphorus content from 0.002% to 0.014% had a large effect on radiation sensitivity but that a further increase to 0.024% produced little additional effect. The difference in radiation sensitivity found between plates V61 and V63 at 0.15% Cu is about the same as that found between similar plates (0.006% and 0.021% P) containing only 0.008% Cu [1] (see Table 4). In Fig. 10, a different trend is observed for copper content. Here, an increase from 0.045% to 0.16% Cu resulted in little effect on radiation sensitivity; however, a large effect was produced by a further increase to 0.30% Cu. In this instance, the contribution of sulfur content to radiation resistance must be acknowledged. Unlike the high-sulfur-content Series V7X, the low-sulfur-content Series 38X and 39X plates (Table 4) [1] studied previously did show an appreciable elevation in radiation sensitivity with an increase in copper from 0.002% to 0.20%. Thus, an effect of sulfur content on the copper contribution to radiation sensitivity is indicated.

It is noted that observations for plate Series V6X and Series V7X are mutually reinforcing. The relative performances of plate V75 and plate V77, for example, confirm the

relative performances of plates V63 and V65 in terms of the trend with phosphorus content. Likewise, the performances of plates V73 and V75 are consistent with those of plate V65 and V67 relative to the trend with copper content.

Upper-Shelf Reduction

Radiation-induced reductions in upper-shelf level (Fig. 11) were less pronounced than the radiation-induced elevations in transition temperature; nonetheless, a parallelism in upper-shelf change with increasing impurities content is illustrated. Phosphorus content again appears to be most influential in the range 0.002% to 0.014%; copper content appears most influential in the range 0.16% to 0.30%. As one result, plate V61 with 0.15% Cu and 0.002% P had less of an upper-shelf reduction than plate V71 with 0.045% Cu and 0.016% P.

Figure 11 also shows a smaller radiation effect for the higher-sulfur-content plate Series V7X than for plate Series V6X. However, on a percentage basis, the reductions in upper-shelf level appear to be almost the same. (Note that plates V63 and V73 and plates V67 and V77 can be compared directly.) The data in turn raise the question of the most applicable and most meaningful method for assessing the reduction, percentage reduction or absolute reduction. In support of the former, resistance to radiation is suspected of being partly a function of the initial (preirradiation) upper-shelf level, with steels having the higher levels showing the greater propensity to change. The relative performance of the LT vs TL orientations of the ASTM A302-B reference plate [6] also suggest such a relationship.

To achieve full qualification of the effects of phosphorus and copper on postirradiation upper-shelf retention, it is clear that an evaluation of certain plates at "matching embrittlement levels" will have to be made. For example, this would involve the irradiation of plates V61 and V63 to fluences A and B, respectively, such that they would exhibit the same transition-temperature increase, e.g., 60°C (110°F). If a difference in upper-shelf reduction is then observed, the actual role of phosphorus content will be established. Lacking such a comparison at present, it is unclear whether the difference in upper-shelf retention is due directly to the difference in phosphorus content or to the difference in "damage level" brought about by the change in phosphorus content.

Transition-Temperature Recovery

Figures 9 and 10 illustrate the effectiveness of 343°C (650°F)—168 h annealing for the various compositions. The two plates having the lowest copper and phosphorus contents exhibit the greatest transition-temperature recovery; however, their performances appear only slightly superior to the remaining materials in their series. The V6X series plates and the V7X series plates also appear comparable. Accordingly, the data demonstrate that the effectiveness of 343°C (650°F) annealing is relatively independent of phosphorus, copper, or sulfur content. Of special importance, it is noted that the transition-temperature recoveries exhibited by the two series are relatively independent of the magnitude of the transition-temperature elevation by irradiation. The difference in elevation in some cases approaches a factor of 2. This independence, in turn, suggests that absolute recovery is quite independent of fluence level. On the other hand, the data trends for percentage recovery suggest that the effectiveness of 343°C (650°F) annealing decreases with increasing fluence as well as with increasing impurities content.

Figures 9 and 10 give specific examples of equal transition-temperature elevations which permit a direct assessment of phosphorus and copper influences on recovery. Plates V63 and V65 with 0.15% Cu and plates V75 and V77 with 0.30% Cu exhibit about the same response to annealing even though their phosphorus contents differ (0.014% vs 0.024% P). Some detrimental effect of increased copper content (0.045% vs 0.16% Cu), on the other hand, is indicated by the performance of plates V71 and V73.

Figure 12 describes the relative benefits of a 399°C (750°F) heat treatment over a 343°C (650°F) heat treatment for five of the plates. Values given for recovery are very approximate because of the limited number of specimens tested. Regardless, the data demonstrate greater recovery with 399°C (750°F) annealing in each instance. Moreover, four of the plates have comparable recovery in spite of differences in initial transition-temperature elevation. That is, annealing response would again appear to be fairly independent of the prior embrittlement condition. The reason for the higher recovery by plate V63 is not clear. It was noted in Fig. 3 that tests were not conducted below the 81-J (60 ft-lb) energy level. However, projections based on the available data describe a recovery in excess of 97°C (175°F).

Finally, it is observed in Fig. 11 that 427°C (800°F)—168 h annealing of one high-copper-, high-phosphorus-content plate was insufficient to produce full transition-temperature recovery.

Upper-Shelf Recovery

Unlike transition-temperature recovery with annealing, full upper-shelf recovery was obtained in all but two instances. The exceptions were plates V67 and V75, annealed at 343°C (650°F). With plate V67, there is little doubt that the indication of incomplete upper-shelf recovery is correct, since duplicate tests of 343°C (650°F) annealing response were made (two separate radiation experiments). With plate V75, on the other hand, it is quite possible that a bias in the data scatter is providing a false indication (Fig. 7). The suspicion of a false indication by the limited data is reinforced by the full recovery exhibited by plate V77.

From the 343°C (650°F) annealing results, it is tentatively concluded that a copper content of 0.30% is detrimental to upper-shelf recovery for steels having sulfur contents on the order of 0.017% but not for steels having a sulfur content on the order of 0.029%. The relative performances of plates V65 and V67 and of plates V73 and V77 support this conclusion. By the same token, a "high" sulfur content appears beneficial to annealing response. The data also suggest that phosphorus content has neither a positive nor a negative effect on upper-shelf recovery. In this case, biased data scatter is taken to be a correct assumption for plate V75.

DISCUSSION

The exploratory investigation has yielded several important determinations on the role of copper, phosphorus, and sulfur impurities on irradiation and annealing response and on annealing recovery characteristics per se. The observations also point the way for needed

follow-on investigations such as the development of plate comparisons at "matching embrittlement levels" and at lower fluences in the case of the higher impurities contents. A need for assessing copper-content effects at the lower of the two sulfur contents and clarification of the contribution of sulfur to both irradiation and annealing response is also shown. Further investigations focusing on these needs are under consideration.

For operating reactor vessels having relatively high sensitivity to radiation embrittlement, the results of the present study suggest that a 343°C (650°F) heat treatment has mixed promise for vessel embrittlement relief. Whereas high upper-shelf recovery was found in most cases, only limited transition-temperature recovery was observed. Accordingly, the determination of steel reembrittlement trends following an anneal will be critically important to the assessment of the practicality of the 343°C (650°F) method. Cyclic irradiation and annealing studies are currently in progress at NRL under sponsorship of the Nuclear Regulatory Commission (NRC). The initial report of findings from these studies is expected in 1978.

CONCLUSIONS

An exploratory investigation has been made on the radiation resistance and postirradiation heat-treatment recovery of A302-B steel as functions of copper, phosphorus, and sulfur content. Primary observations and conclusions of the study are:

1. Radiation-embrittlement sensitivity, in terms of transition-temperature elevation, generally increased with increased copper and phosphorus content and with decreased sulfur content.
2. Radiation-embrittlement sensitivity, in terms of the upper-shelf reduction, also increased with increased copper and phosphorus content and with decreased sulfur content.
3. The effect of increasing phosphorus content on radiation sensitivity was observed predominantly in the range of 0.002% to 0.014% P, compared to the test matrix range of 0.002% to 0.024% P.
4. The effect of increasing copper content on radiation sensitivity was observed predominantly in the range of 0.16% to 0.30% Cu, compared to the test matrix range of 0.045% to 0.30% Cu.
5. A high sulfur content (0.029% S) appears to reduce the detrimental effect of copper content on radiation sensitivity.
6. A 343°C (650°F) 168-h heat treatment produces only small transition temperature recovery (i.e., 22° to 39°C, 40° to 70°F) regardless of the level of copper, phosphorus, and sulfur impurities and the magnitude of the transition-temperature elevation by irradiation. A detrimental effect on recovery of a 0.16% Cu content compared to a 0.045% Cu content is suggested by one set of data.
7. A 343°C (650°F) 168-h heat treatment produces full upper-shelf recovery for most of the impurity compositions investigated.
8. A copper content of 0.30% but not 0.16% is detrimental to upper-shelf recovery for steels containing about 0.017% S.

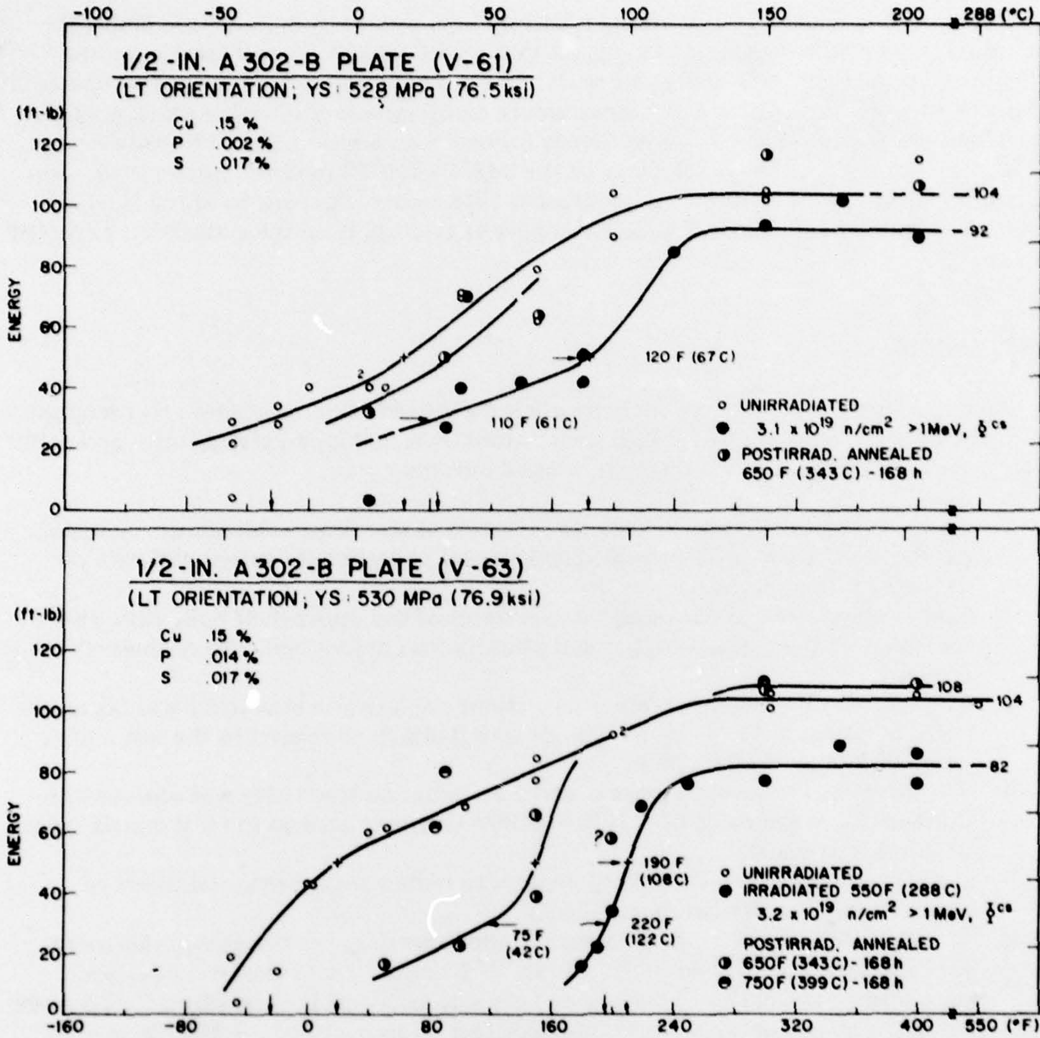

Fig. 3 — Charpy-V notch ductility of plates V61 and V63 after irradiation and after postirradiation heat treatment.

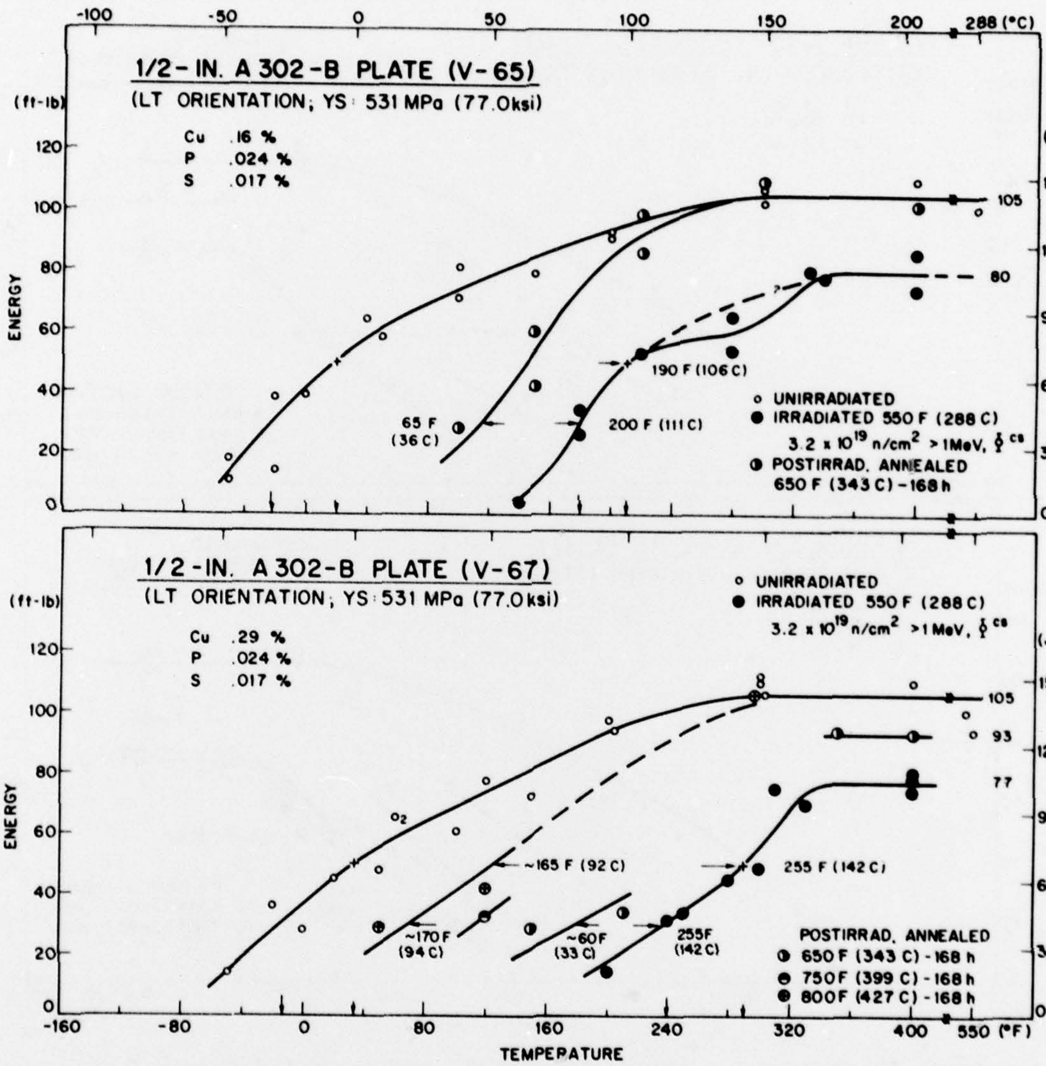

Fig. 4 — Charpy-V notch ductility of plates V65 and V67 after irradiation and after postirradiation heat treatment.

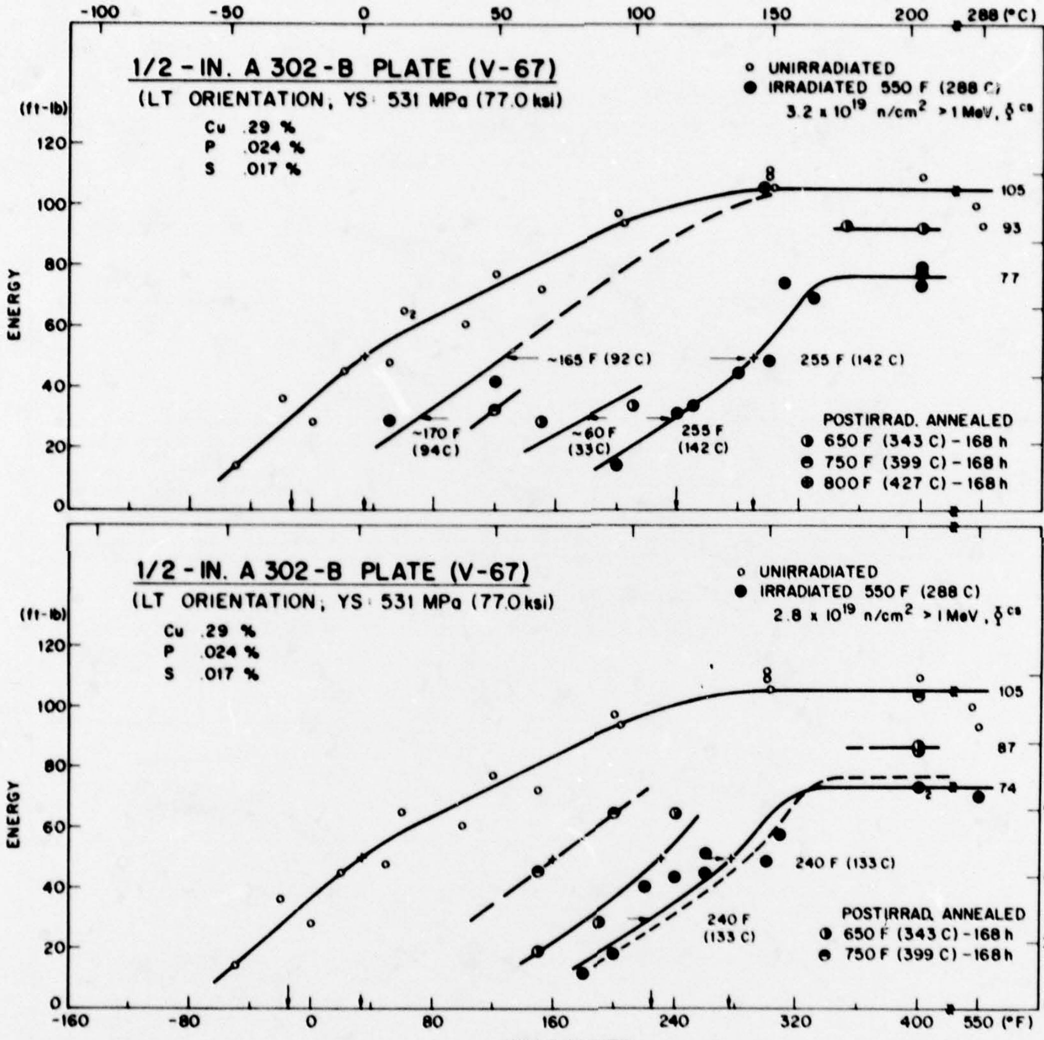

Fig. 5 — Charpy-V notch ductility of plate V67 after irradiation and after postirradiation heat treatment. The upper graph refers to Irradiation Experiment No. 1; the lower graph refers to Irradiation Experiment No. 2. The as-irradiated condition curve from the upper graph is reproduced in the lower graph (see dashed curve) for reference.

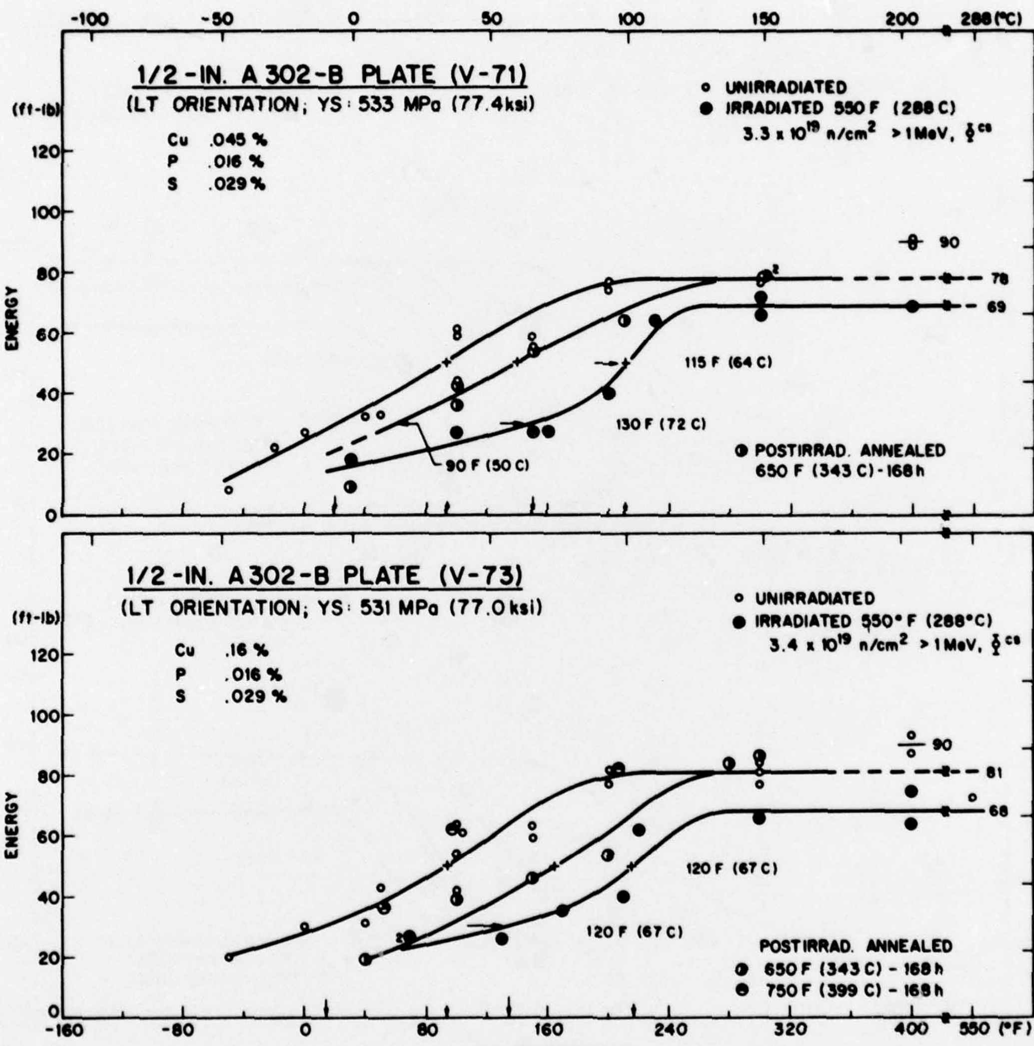

Fig. 6 — Charpy-V notch ductility of plates V 71 and V73 after irradiation and after postirradiation heat treatment.

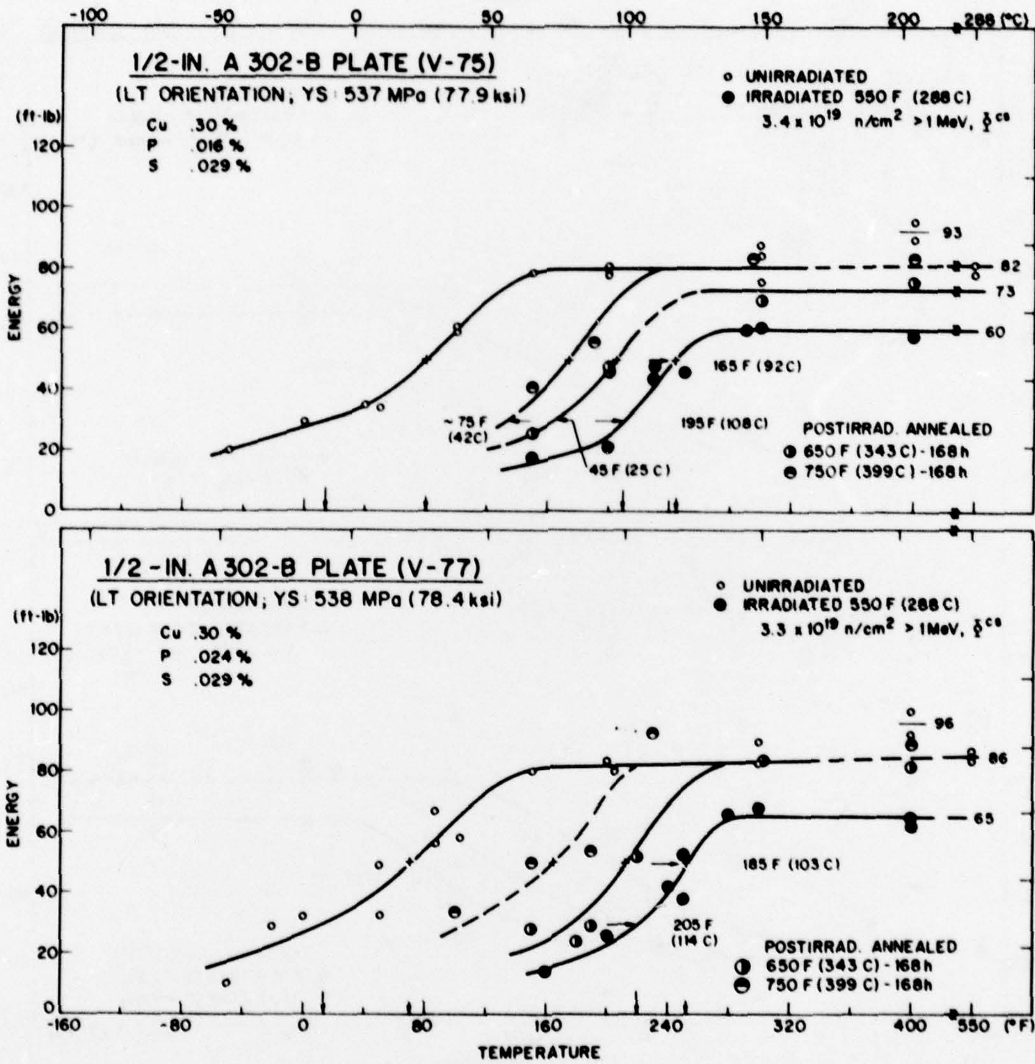

Fig. 7 — Charpy-V notch ductility of plates V75 and V77 after irradiation and after postirradiation heat treatment.

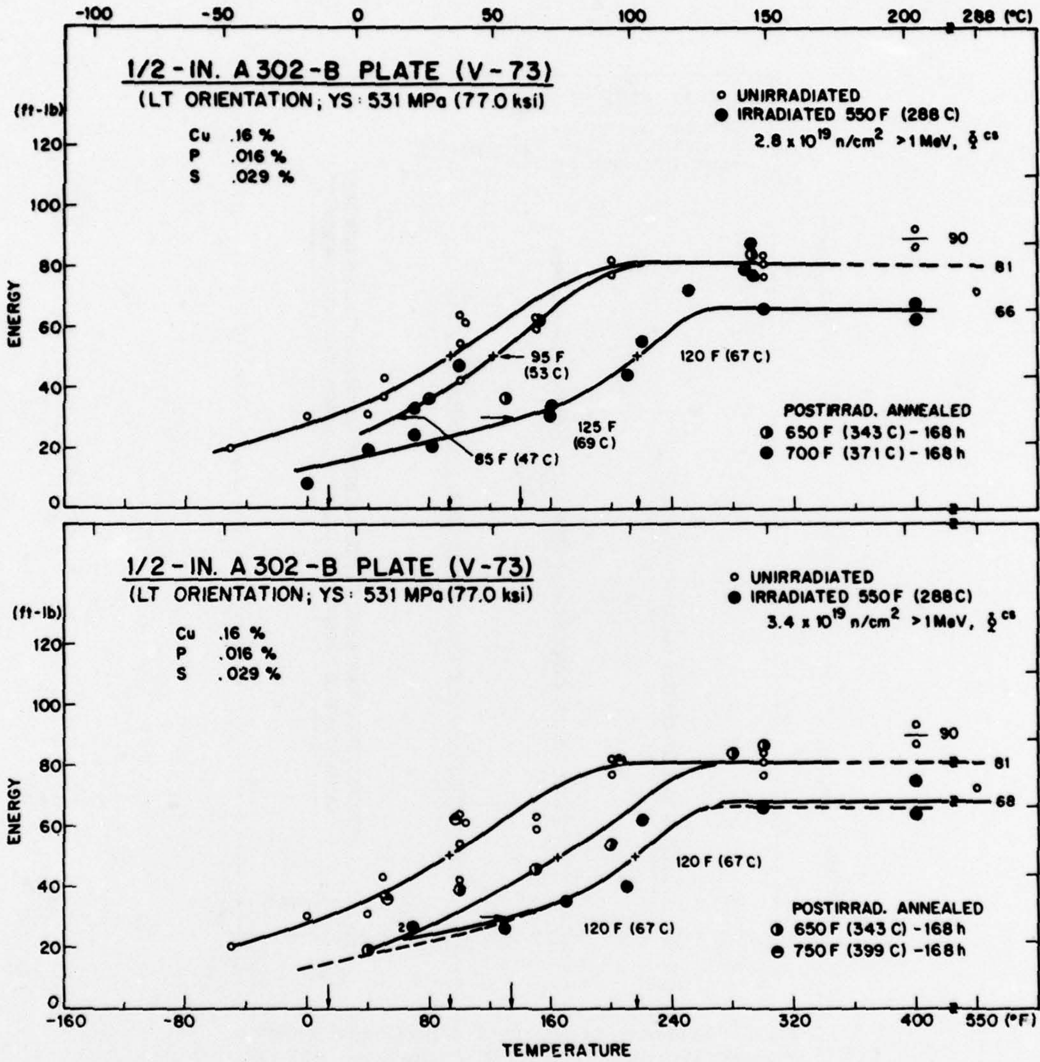

Fig. 8 — Charpy-V notch ductility of plate V73 after irradiation and after postirradiation heat treatment. The upper graph refers to Irradiation Experiment No. 1; the lower graph refers to Irradiation Experiment No. 2. The as-irradiated condition curve from the upper graph is reproduced in the lower graph (see dashed curve) for reference.

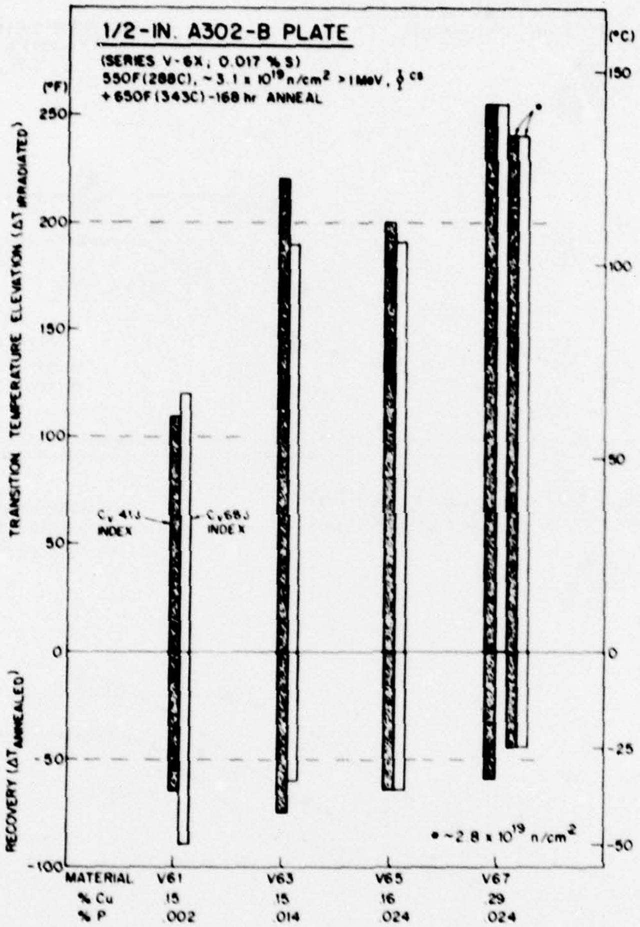

Fig. 9 — Summary of Charpy-V transition-temperature changes (41-J and 68-J indices) of plate Series V6X with 288°C (550°F) irradiation and with 343°C (650°F) postirradiation heat treatment.

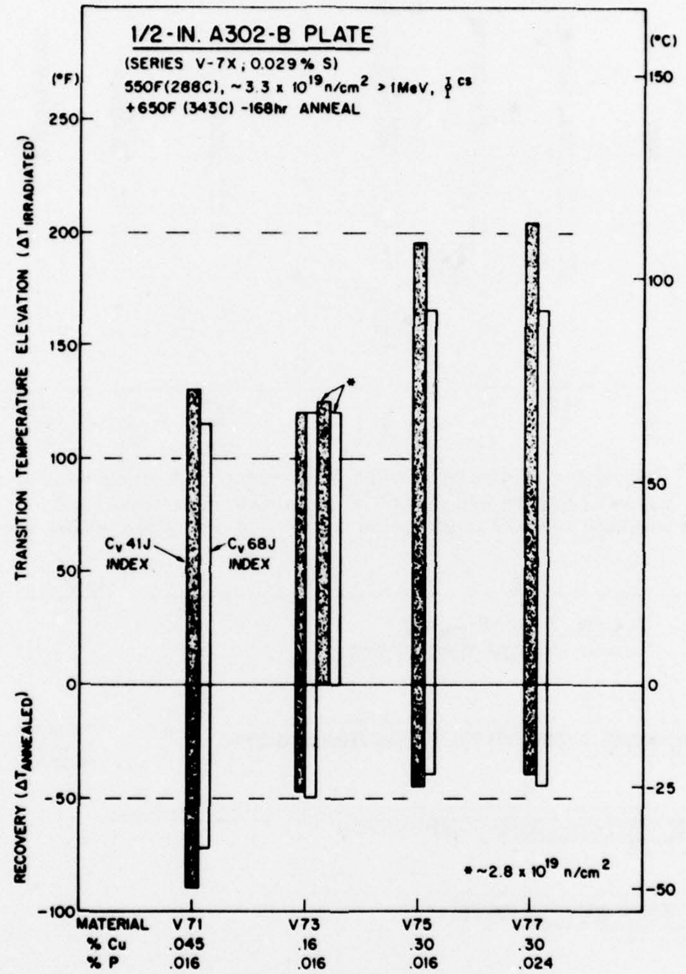

Fig. 10 — Summary of Charpy-V transition-temperature changes (41-J and 68-J indices) of plate Series V7X with 288°C (550°F) irradiation and with 343°C (650°F) postirradiation heat treatment.

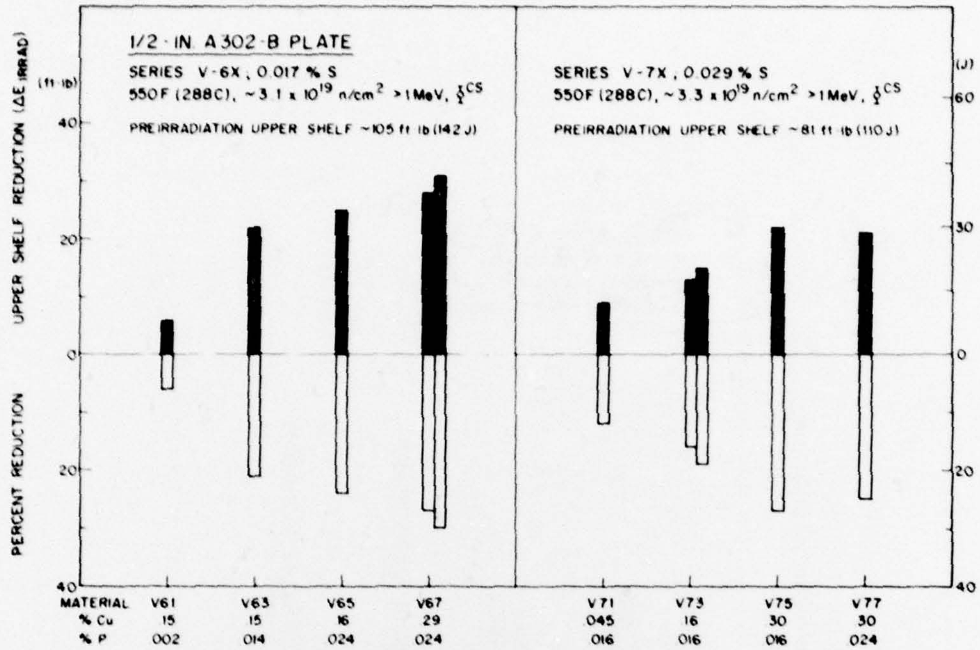

Fig. 11 — Comparison of Charpy-V upper-shelf energy reductions of plate Series V6X and plate Series V7X after 288°C (550°F) irradiation. The upper portion of the graph shows the absolute reduction; the lower portion of the graph shows the percentage reduction.

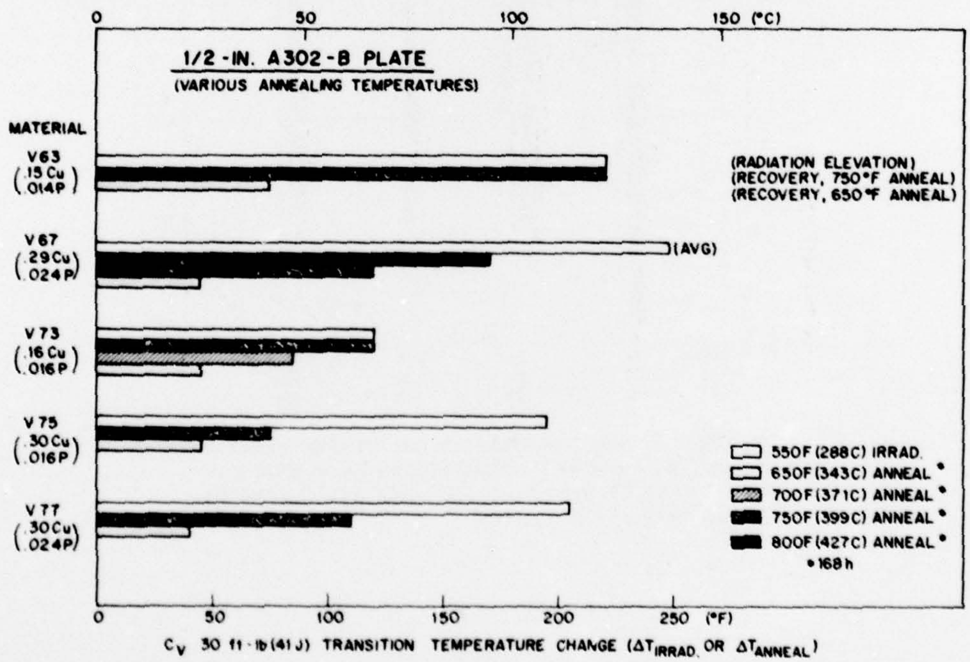

Fig. 12 — Comparison of Charpy-V transition-temperature recovery (41-J index) produced by various postirradiation heat-treatment temperatures. The initial radiation-induced elevations in transition temperature are also shown for reference.

Table 4 — Charpy-V Notch Ductility of A302-B Steel Plates Before and After Irradiation and Postirradiation Heat Treatment

Plate Code	Exp. No.	Initial Properties: Φ^{cs}[a] ($\times 10^{19}$)	C_v 41 J[b] (°C)	C_v 41 J[b] (°F)	C_v 68 J[c] (°C)	C_v 68 J[c] (°F)	C_v USE[d] (J)	C_v USE[d] (ft-lb)	288°C (550°F) Irradiation: ΔC_v 41 J (Δ°C)	ΔC_v 41 J (Δ°F)	ΔC_v 68 J (Δ°C)	ΔC_v 68 J (Δ°F)	ΔC_v USE (ΔJ)	ΔC_v USE (Δft-lb)
V61	1	3.1	−32	−25	18	65	141	104	61	110	67	120	8	6
V63	1	3.2	−32	−25	− 7	20	141	104	122	220	106	190	30	22
V65	1	3.2	−29	−20	− 7	20	142	105	111	200	106	190	34	25
V67	1	3.2	−26	−15	2	35	142	105	142	255	142	255	38	28
V67	2	2.8	−26	−15	2	35	142	105	133	240	133	240	42	31
V71	2	3.3	− 7	20	35	95	106	78	72	130	64	115	12	9
V73	2	3.4	− 9	15	35	95	110	81	67	120	67	120	18	~13
V73	1	2.8	− 9	15	35	95	110	81	69	125	67	120	20	15
V75	2	3.4	− 9	15	27	80	111	82	108	195	92	165	30	22
V77	2	3.3	− 9	15	21	70	114	84	114	205	103	185	29	21
40B(1)	A	~3.3	−18	0	e	e	24	75	0	0	e	e	~0	~0
40C(1)	A	~3.3	− 7	20	e	e	24	75	44	80	e	e	~0	~0
38A(1)	B	~2.5	−40	−40	e	e	49	120	0	0	e	e	~0	~0
38B(1)	B	~2.5	−48	−55	e	e	60	140	31	55	e	e	~14	~10
39A(1)	B	~2.5	−46	−50	e	e	52	125	0	0	e	e	~0	~0
39B(1)	B	~2.5	−46	−50	e	e	57	135	44	80	e	e	~7	~5

Plate Code	Exp. No.	Φ^{cs}[a] ($\times 10^{19}$)	343°C (650°F) Postirradiation Heat Treatment: ΔC_v 41 J (Δ°C)	ΔC_v 41 J (Δ°F)	ΔC_v 68 J (Δ°C)	ΔC_v 68 J (Δ°F)	ΔC_v USE (Recovery) (ΔJ)	ΔC_v USE (Recovery) (Δft-lb)
V61	1	3.1	36	65	53	95	F	F
V63	1	3.2	42	75	33	60	F	F
V65	1	3.2	36	65	36	65	F	F
V67	2	2.8	25	45	25	45	18	13
V67[f]	2	2.8	~67	~120	64	115	F	F
V67[f]	1	3.2	~69	~125	e	e	e	e
V67[g]	1	3.2	94	170	92	165	F	F
V63[e]	1	3.2	~F	~F	F	F	F	F
V71	2	3.3	50	90	39	70	F	F
V73	2	3.4	25	45	28	50	F	F
V73[f]	2	3.4	~F	~F	~F	~F	F	F
V73[i]	1	2.8	47	85	53	95	F	F
V75	2	3.4	25	45	22	40	18	13
V75[f]	2	3.4	~42	~75	~39	~70	F	F
V77	2	3.3	22	40	25	45	F	F
V77[f]	2	3.3	~61	~110	~50	~90	F	F

[a] Φ^{cs} (>1 MeV); Φ^{cs} > 0.1 MeV = 2.91 Φ^{cs} > 1 MeV
[b] C_v 30 ft-lb transition temperature
[c] C_v 50 ft-lb transition temperature
[d] C_v upper-shelf energy
[e] Not available or not determined.
[f] 399°C (750°F) 168 h postirradiation heat treatment.
[g] 427°C (800°F) 168 h postirradiation heat treatment.
[h] 371°C (700°F) 168 h postirradiation heat treatment.
F = Full recovery

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